LA-UR- 11-03126

Approved for public release;
distribution is unlimited.

Title: Nuclear Weapon Fundamentals (U)

Author(s): John J. Vandenkieboom

Intended for: Nuclear Nonproliferation Workshop (NNPW)
DOE/HQ Washington, D.C.
June 14-17, 2011

Abstract:

Nuclear Weapon Fundamentals (U)

John J. Vandenkieboom

Nuclear weapons operate in an extreme range of conditions. The physical processes are highly-nonlinear and tightly coupled. This talk is meant to introduce the basic physics concepts that are involved when one begins to address the design issues associated with weapons. It starts with basic nuclear physics and works itself into discussion of the historical development of nuclear weapon concepts. Both nuclear and nonnuclear testing activities are briefly reviewed. (U)

Nuclear Weapon Fundamentals

Presented at

Nuclear Nonproliferation Workshop

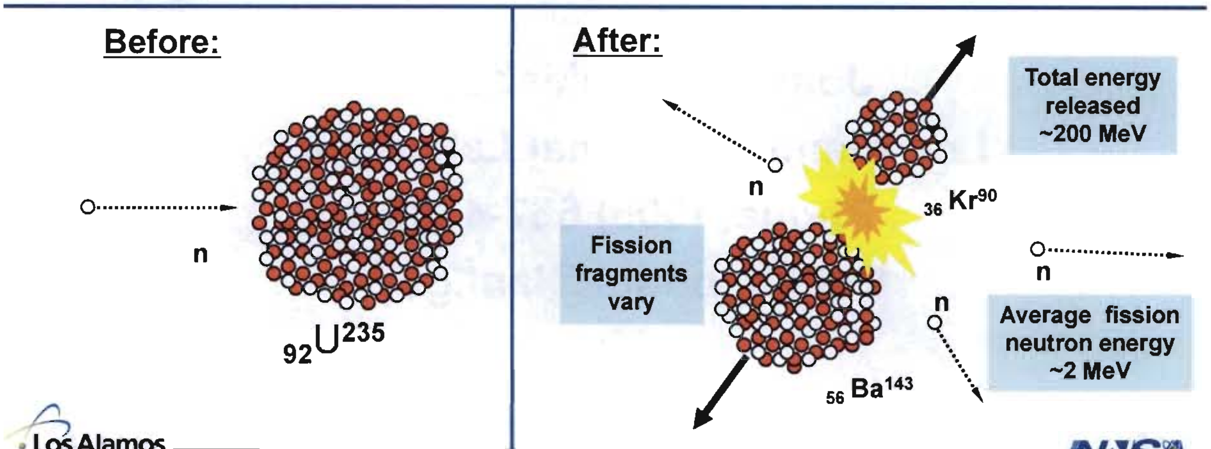
John Vandenkieboom
Los Alamos National Laboratory
Phone: (505) 667-4398
E-mail: boom@lanl.gov

Outline

1. Review
2. Fission weapons
3. Advanced weapons
4. Weapon design and development

Fission (Neutron-induced)

- One of many possible reactions that can occur when a neutron interacts with ^{235}U, ^{239}Pu, or another fissionable nuclei
- Large energy release per reaction
- Additional neutrons released (opens possibility of a fission chain reaction)



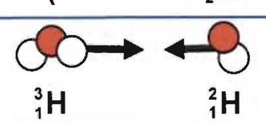
Fusion Reactions

- Can be thought of as the opposite of fission
- High temperatures ("thermonuclear") and densities needed for reaction to proceed
- Large energy release per reaction
- High-energy neutrons can be released

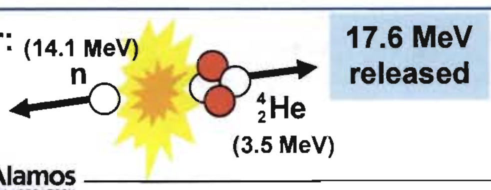
Example: $^{3}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + n$

$(T + D \rightarrow ^{4}_{2}He + n)$

Before:



After:



Other reactions of interest:

$D + D \rightarrow ^{3}_{2}He + n + 3.2\ MeV$

$D + D \rightarrow T + p + 4.0\ MeV$

$D + ^{3}_{2}He \rightarrow p + ^{4}_{2}He + 18.3\ MeV$

$T + T \rightarrow ^{4}_{2}He + 2n + 11.3\ MeV$

Explosively Fissionable Material

- Any material that can be assembled into a supercritical mass, supporting a fast neutron chain reaction
  - » Weapon-grade materials
    - highly enriched uranium, >93% ^{235}U
    - weapons-grade Pu, ^{239}Pu with 6% ^{240}Pu
  - » Alternatives
    - ^{233}U
    - reactor-grade Pu
    - uranium with < 93% ^{235}U
    - fissible isotope ^{237}Np (neptunium)

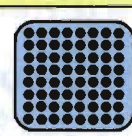
Plutonium

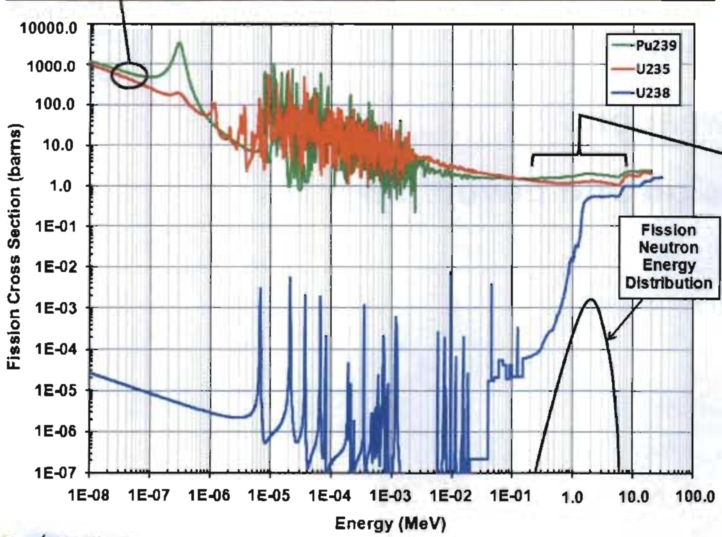
- Essential material to make a nuclear weapon
  - » Hypothetically, 25 kg ^{235}U or 4 kg Pu can be enough

Fundamental nuclear properties determine utility of material in weapons

Light water reactors moderate (or slow) fission neutrons down to low energies (0.05 eV) where the fission cross section is large

→ Allows the use of low enrichment fuel





Fission cross section is more than two orders of magnitude smaller at fission neutron energies (~2 MeV)

↓

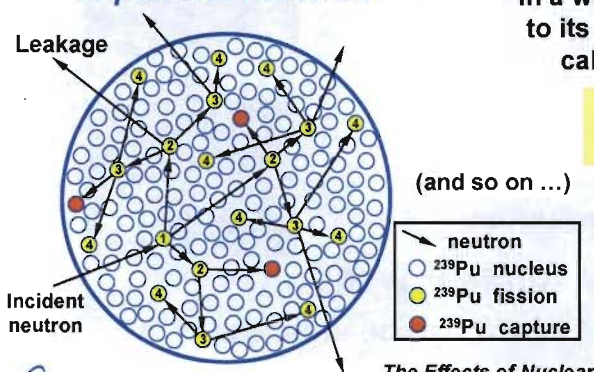
Necessitates the much higher enrichments in nuclear weapons

Supercritical Mass

Criticality: **measure of how the number of neutrons (and energy release) in the system (e.g., nuclear weapon or reactor) will change over time**

In a supercritical system the fission neutron production rate is greater than the neutron loss rate from leakage and other reactions ➡ ***Neutron Production > Loss*** ➡ **number of neutrons (and energy release) increases with time**

Exponential Growth:



In a weapon, the time from birth of fission neutron to its subsequent absorption in a fission event is called the *generation time*: ~10^{-8} s (1 shake)

Neutrons (or fissions) at generation "n" ➡ $N_n = N_0 e^n$

n	Time (μs)	Fissions	Energy (kt)
50	0.50	5.2×10^{21}	0.04
55	0.55	7.7×10^{23}	5.3
60	0.60	1.1×10^{26}	787

The Effects of Nuclear Weapons, Glasstone and Dolan (1977)

Very short timescale!

Outline

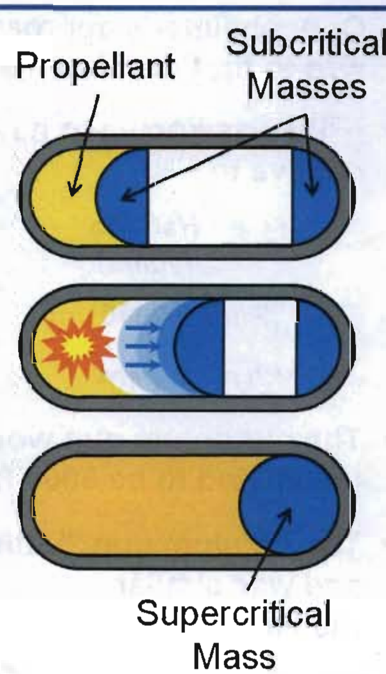
1. Review of nuclear physics
2. Fission weapons
3. Advanced weapons
4. Weapon design and development

Fission Weapons

- A system for rapidly transforming a mass of "explosively fissionable material" from a subcritical configuration to a highly supercritical configuration, passing through critical along the way
- Initiation of a runaway neutron chain reaction while in supercritical configuration
- Maintain supercritical configuration long enough to allow large fission energy release

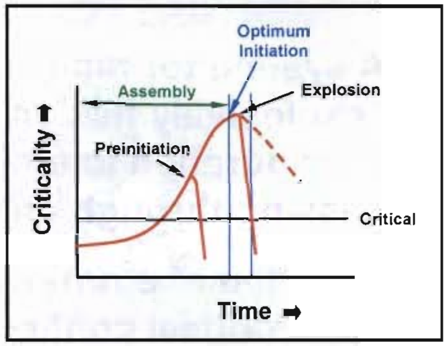
Gun Assembly

- Assemble subcritical masses together into a supercritical mass using propellant driven gun
- Simple design based on familiar "gun" technology
- Inefficient use of material since it is used at normal density



Preinitiation

- **A supercritical mass of "explosively fissionable material" cannot be protected against accidental detonation**
- **Within a short time, background neutron sources will start a neutron chain reaction**
  1. ***Neutrons from cosmic ray interactions***
  2. ***Spontaneous fission neutrons***
  3. ***(α,n) reactions with light element impurities***



- **Assembly from a subcritical to supercritical configuration takes place over a finite time interval**
- **During the time interval from critical to maximum supercriticality, a weapon is susceptible to early neutron initiation (preinitiation) resulting in less than optimal yield (fizzle yield)**

Manhattan Project

- **Oppenheimer's approach to gun weapon design prior to mid-1944 was to first develop the plutonium gun, code named "Thin Man"**
- **^{239}Pu was known to have a much higher neutron background rate relative to ^{235}U**

	Half-life (years)	*Spontaneous Fission Neutron Production Rate (neutrons/kg/s)*	
$^{239}_{94}$Pu	24,110	~20	← Over three orders of magnitude higher
$^{235}_{92}$U	7 x 10^8	~0.01	

- **The plutonium gun would require a faster assembly speed (estimated to be 3000 ft/s, 0.9 mm/μs)**
- **The uranium gun "Little Boy" presented less of a challenge and was similar to standard artillery technology available at the time (1000 ft/s, 0.3 mm/μs)**

Manhattan District History - Project Y - The Los Alamos Project, **LAMS-2532 (Vol. 1)**

First Plutonium Production

By February 1941, ^{239}Pu was first produced and isolated at Berkeley, California (Seaborg's group).

$$^{238}_{92}\mathrm{U} + ^{2}_{1}\mathrm{H} \rightarrow \mathrm{n} + ^{239}_{93}\mathrm{Np} \xrightarrow{\beta^-} ^{239}_{94}\mathrm{Pu}$$

$^{239}_{93}$Np: $T_{1/2}$ 2.4 Days; $^{239}_{94}$Pu: $T_{1/2}$ 24,110 Years

Deuterons generated by the Berkeley 60 inch cyclotron were used to irradiate a ^{238}U target, resulting in the production of a small quantity of ^{239}Pu (< 1μg).

- **Deuteron irradiation had a low associated neutron flux**

Reactor Plutonium Production

- **Reactors produce large neutron fluxes, realizing much higher ^{239}Pu production rates**
- **Large neutron flux also results in production of ^{240}Pu via additional neutron capture reactions**
- **^{240}Pu has high spontaneous fission rate, resulting in a large neutron background**

CP-1 Reactor
Univ. of Chicago
2 Dec 1942

X-10 Reactor
Oak Ridge, TN
4 Nov 1943

B Reactor
Hanford, WA
27 Sep 1944

$$^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \xrightarrow{\beta^-} ^{239}_{93}\mathrm{Np} \xrightarrow{\beta^-} ^{239}_{94}\mathrm{Pu}$$

$^{239}_{92}$U: $T_{1/2}$ 24 Minutes; $^{239}_{93}$Np: $T_{1/2}$ 2.4 Days; $^{239}_{94}$Pu: $T_{1/2}$ 24,110 Years

$$^{239}_{94}\mathrm{Pu} + \mathrm{n} \rightarrow ^{240}_{94}\mathrm{Pu}$$

$^{240}_{94}$Pu: $T_{1/2}$ 6535 Years

Thin Man Crisis

- First samples of reactor produced Pu were received from Oak Ridge for analysis at Los Alamos in April 1944
- Analysis by Segre's group showed high neutron background rate due to spontaneous fission in ^{240}Pu (5X Seaborg's initial sample)
- Assembly speed of 3000 ft/s for Thin Man wasn't fast enough and the plutonium gun was abandoned
- Los Alamos workforce radically refocused toward development of the implosion weapon (LA staff increased from 1100 ⇒ 2500 in less than a year)

Dwight Young Cabin - Tech Area 18, LANL

Neutron background rates:
HEU : ~1 neutron/kg/second
WGPu : ~60,000 neutrons/kg/second
RGPu : ~300,000 neutrons/kg/second

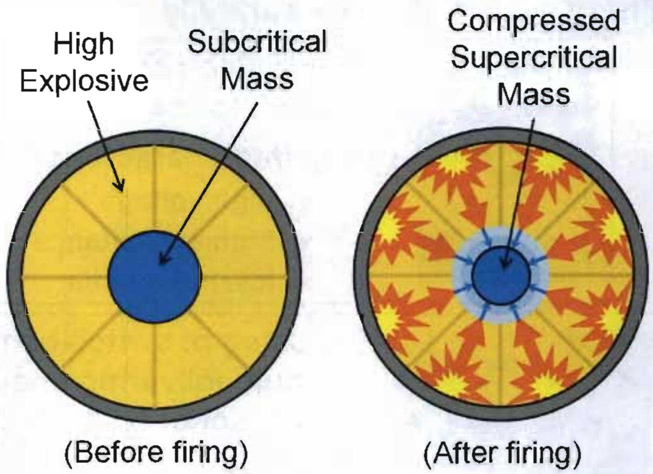
Critical Assembly - A Technical History of Los Alamos during the Oppenheimer Years, 1943-1945, **republished by Cambridge University Press in 2004.**

Little Boy

Untested prior to being dropped over Hiroshima on August 6, 1945 (15 kt)

Implosion Assembly

- Complex design – involves precision application of high explosive (HE)
- Symmetrical explosion of the HE implodes pit, compressing fissile material into a supercritical configuration
- More efficient use of material than gun-assembled weapon
- Fast assembly speed allows use of plutonium

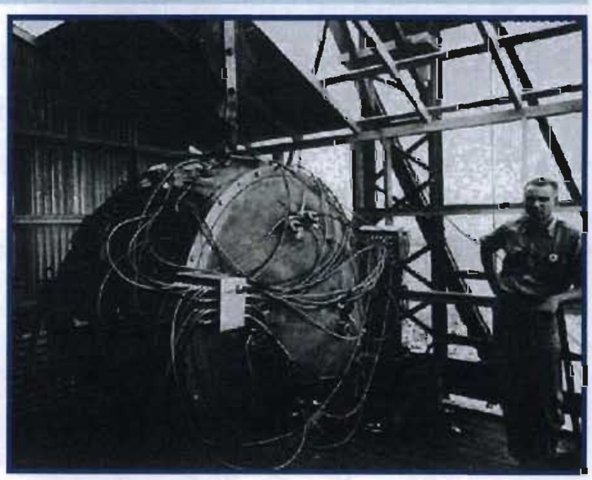


HE detonation waves propagate at speeds up to 8 km/s (8 mm/μs) and can drive metal plates at speeds up to 4 km/s (4 mm/μs)

Implosion Weapon

Use symmetric high explosive detonation to drive the pit into a highly supercritical configuration

- Firing system
- Detonators
- High explosive lenses
- Main HE charge
- Pit containing active nuclear material
- Neutron initiation source



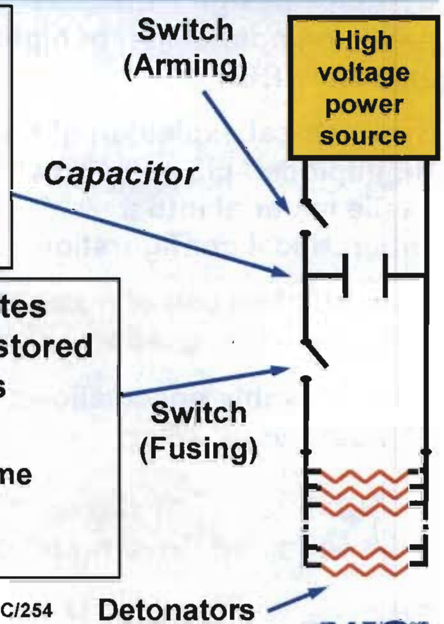
Firing System Components

Firing system delivers carefully controlled electrical pulse to detonators

- Stores electrical energy for delivery to the detonators
- Required characteristics
  - » high voltage
  - » high capacitance
  - » low inductance

Krytrons, sprytrons, triggered spark gaps

- Closing of switch completes circuit delivering energy stored in capacitor to detonators
- Required characteristics
  - » short commutation time
  - » high voltage
  - » high capacitance

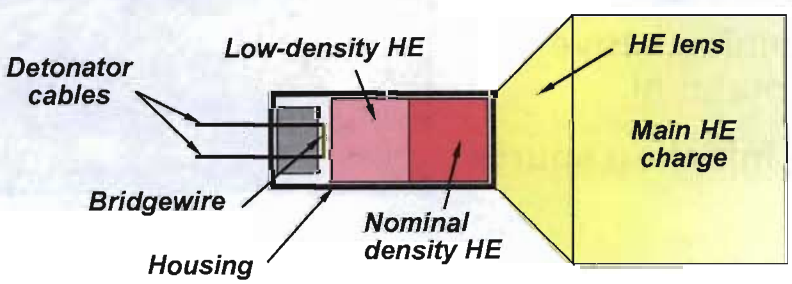


IAEA Nuclear Suppliers Group (NSG) Dual-use List, INFCIRC/254

Exploding Bridgewire (EBW) Detonator

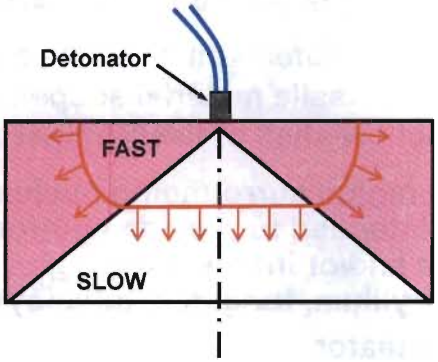
Detonators are used to initiate larger high explosive charges and operate by converting stored capacitor electrical energy into a high explosive detonation

- Pulse of electric current vaporizes thin bridgewire, producing shock wave
- Shock wave initiates adjacent low-density HE pellet
- As the building detonation front propagates, it strengthens in the nominal density HE pellet
- Repeatability must be within small fraction of a second



High Explosive Lenses

- Generate symmetrical controlled detonation wave
- Lenses make use of two high explosives, chosen for their relative detonation velocities, to achieve desired detonation wave



Slow HE component (Baratol)

Fast HE component (Comp-B)

Plane-wave conventional HE lenses

High Explosive (HE) Fabrication

Castable:

HE is melted in a steam-jacketed kettle (TNT: T_{melt} = *80°C*, $T_{ignition}$ = *240°C*). Poured into mold and slowly cooled in a controlled fashion to prevent cracking.

- » *TNT (trinitrotoluene)*
- » *Composition B-3 (60% RDX, 40% TNT)*

HE melting kettle

Plastic-bonded explosive (PBX):

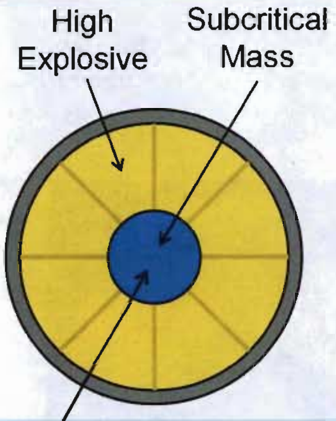
Carefully controlled mixture of HE compound and plastic binder (5-20 weight %) is hydrostatically pressed under heat and a vacuum.

- » *Conventional HE:* HMX or RDX
- » *Insensitive HE:* TATB

Hydrostatic press

Final machining of parts is performed, followed by X-ray inspection for internal voids and cracks

Pit



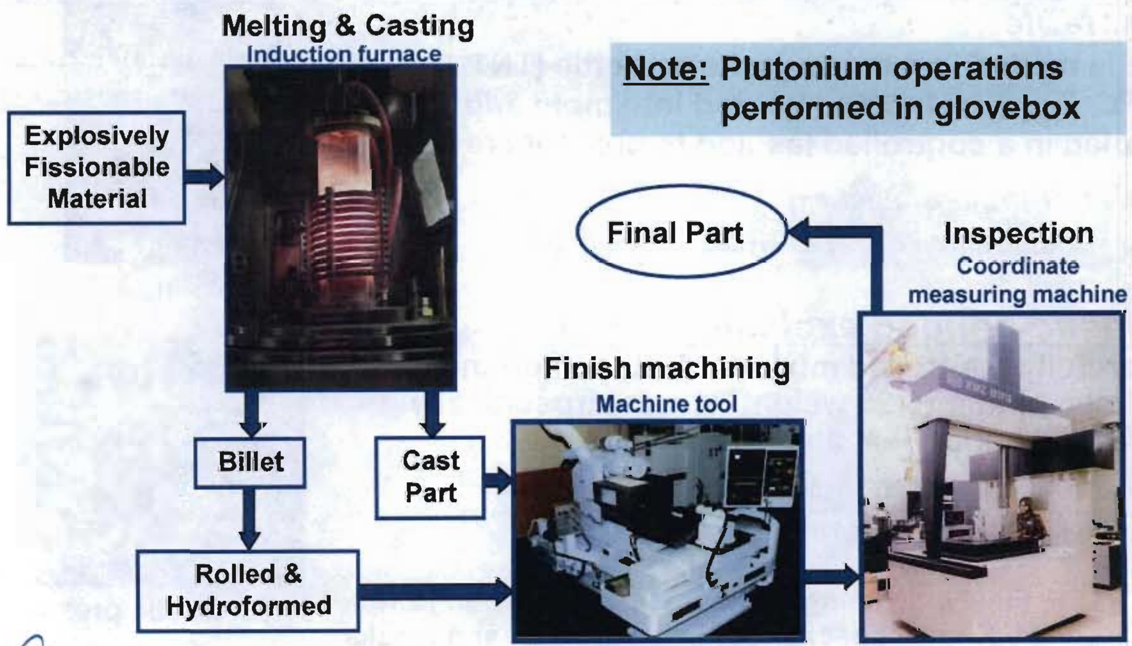
Pit is made up of components located within the inner boundary of the high explosive

Pit may contain:

- Active nuclear material (^{235}U and/or ^{239}Pu) in the form of:
  1. *Solid ball*
  2. *Thin hollow shell*
  3. *Levitated* - pit contains a centrally suspended ball of fissile material
  4. *Split-levitated* - pit contains a central ball of fissile material suspended within a hollow shell of fissile material
- Tamper - region surrounding nuclear material intended to provide neutronic reflection and/or inertial tamping (steel, beryllium, tungsten, tuballoy)
- Internal initiator

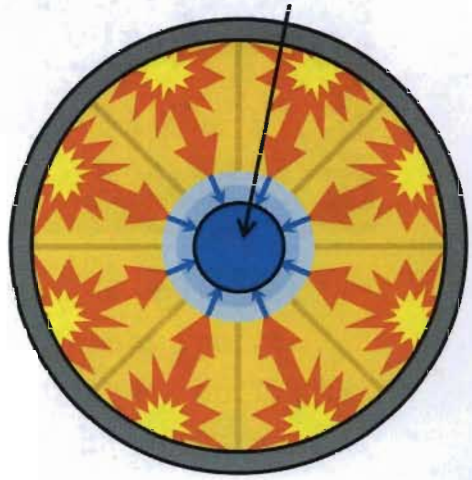
Pit Fabrication

Note: Plutonium operations performed in glovebox



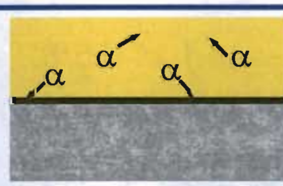
Implosion Assembly – After Firing

- **Following implosion, pit will be highly supercritical**
- **At this time, neutrons must be introduced into pit to begin fission chain reaction (this is called neutron initiation)**
  - » **Internal initiators**
  - » **External initiators**



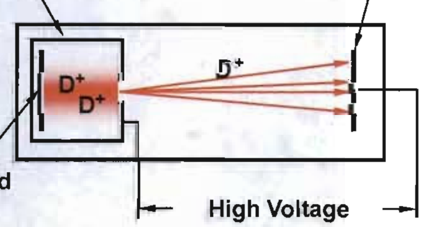
Neutron Initiators

Internal Initiator:
(α,n) reactions between strong α-emitter and a light target element



$${}^{210}_{84}\mathrm{Po} \xrightarrow[138\ \text{days}]{T_{1/2}} {}^{206}_{82}\mathrm{Pb} + \alpha({}^{4}_{2}\mathrm{He}) \Rightarrow \alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + n$$

External Initiator:
Small neutron generator tube producing fusion of deuterium and tritium



Both are radioactive and must be periodically replaced

LA-UR 11-03126

Trinity/Fat Man

Tested in Trinity shot 7/16/45 at Alamogordo; dropped over Nagasaki on 8/9/45 (21 kt)

- Used ~6 kg of Plutonium
- Tuballoy tamper (depleted uranium)
- 32 detonators and associated lenses
- Internal α-n initiator (^{210}Po-Be)

LA-UR 11-03126

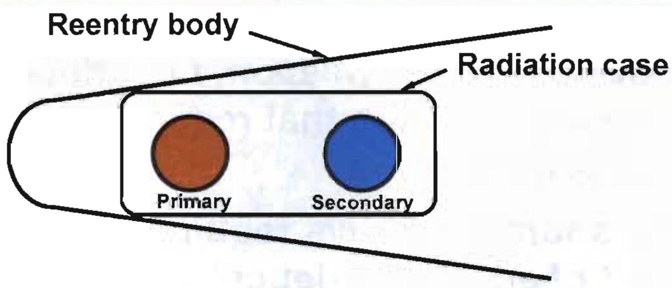
Ivy/King

Tested 11/15/52 at Enewetak
Largest US fission only device (500 kt)

Outline

1. Review of nuclear physics
2. Fission weapons
3. Advanced weapons
4. Weapon design and development

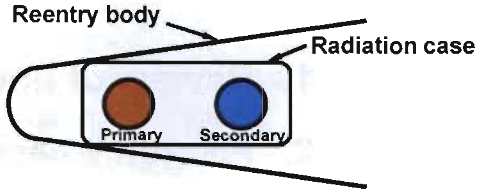
Thermonuclear Weapons



- Thermonuclear weapons have two physically separate stages: a primary and a secondary
- The primary fission stage goes off first, followed by the secondary stage

Radiation Coupling

"Radiation Coupling" refers to the use of x-rays from a fission primary to transport energy for compressing and imploding a secondary



- Thermal radiation energy (x-rays) produced by the primary fission stage is contained by a radiation case
- Radiation case is made of a material opaque to radiation (e.g., lead and uranium)
- X-ray energy contained within radiation case flows toward and around the secondary stage, heating and compressing it

LA-UR 11-03126

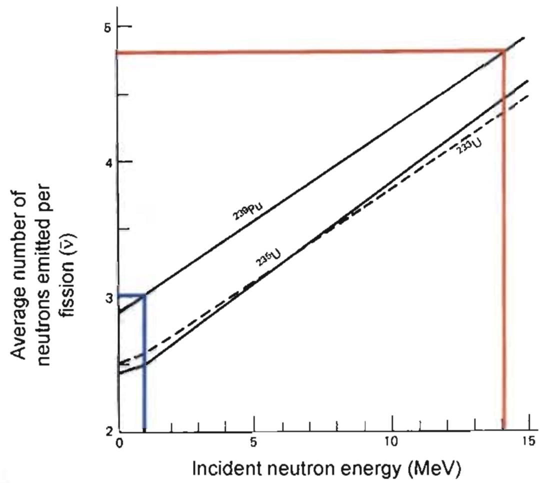
Primary Stage

- In an effective two-stage weapon, the primary is the source of the radiation that reaches and drives the secondary
- An effective source of x-rays requires that a large amount of energy be deposited within a small amount of mass (i.e., high efficiency)

A gun weapon is inefficient and does not make a good primary

Boosted Fission Weapons

- Fusion produces energetic neutrons which can enhance the fission chain reaction. This is called *boosting*.
- Boosting is used in primaries of thermonuclear weapons.



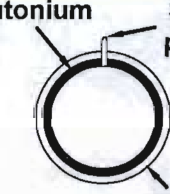
As incident neutron energy increases, the average number of neutrons emitted in the fission event increases

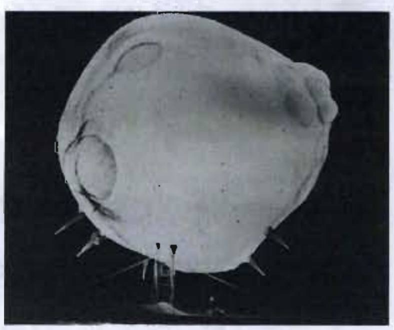
Boosted Fission Weapons

Boosting refers to the use of DT fusion neutrons to enhance the fission chain reaction

- Mixture of deuterium and tritium (boost gas) is introduced from a reservoir to pit's central cavity
- During implosion, boost gas is compressed along with the fissile material
- Driven by energy from fission, D-T fusion occurs, flooding compressed pit with high energy neutrons
- These neutrons produce additional fissions, driving nuclear yield to much higher values

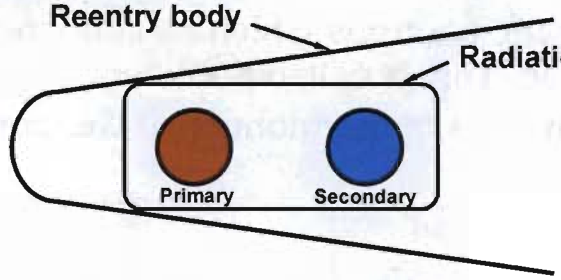
Bulk of the yield is from fission; fusion yield is a few percent of the total





Greenhouse/Item (5/24/51)
First US boosted device (45.5 kt)

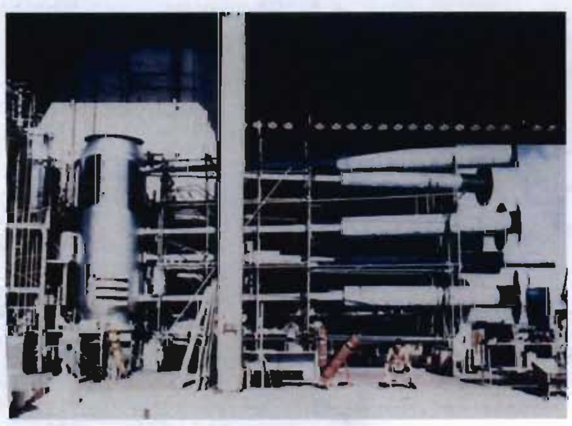
Secondary Stage



The secondary stage can contain:

- **thermonuclear fuel (e.g., ^{6}LiD, gaseous or liquid forms of D and/or T)**
- **fissile or fissionable materials (e.g., enriched or depleted uranium)**

Ivy/Mike: tested 10/31/52 at Enewetak First Multi-Megaton Test, 10.4 Mt



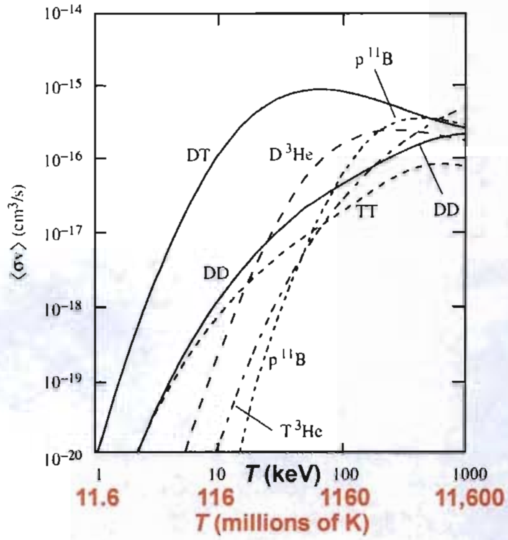
- **"Experimental" thermonuclear device**
- **TN fuel was liquid deuterium**
- **Complex and bulky cryogenic equipment**

Lithium Deuteride as TN Fuel

- Lithium deuteride can be used as a thermonuclear fuel
- While undergoing heating and compression, neutrons are interacting with lithium, creating tritium

$${}^{6}_{3}\mathrm{Li} + \mathrm{n} \longrightarrow \mathrm{T} + {}^{4}_{2}\mathrm{He} + 4.8\ \mathrm{MeV}$$

$${}^{7}_{3}\mathrm{Li} + \mathrm{n} \longrightarrow \mathrm{T} + {}^{4}_{2}\mathrm{He} + \mathrm{n}' - 2.5\ \mathrm{MeV}$$



- Tritium and deuterium subsequently undergo fusion producing thermonuclear burn

Castle/Bravo: tested 2/28/54 at Bikini Largest US detonation at 15 Mt

- Used lithium deuteride as a thermonuclear fuel

During WWII the Allies dropped ~5 Mt (TNT_{eq}) of conventional bombs on Axis forces

Largest Weapon Detonation

- Soviet test at Novaja Zemlya on 30 October 1961
- Fired at: ~58 Mt
- Design yield: 100 Mt

"American Devil in Russian Paradise"

Dr. Edward Teller (5'8") at Snezhinsk (C-70)

Outline

1. Review of nuclear physics
2. Fission weapons
3. Advanced weapons
4. Weapon design and development

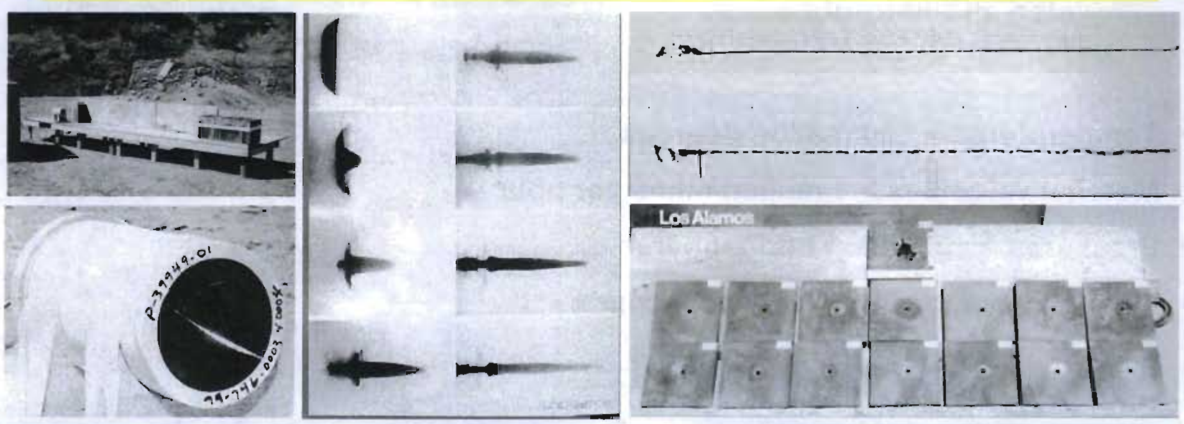
Nonnuclear Hydrodynamic Testing

Hydrotests are instrumented HE-driven experiments used to study the characteristics of a high fidelity primary "mockup" during its implosion phase

Fissile material replaced with a nonfissile surrogate with similar density and other metallurgical properties (e.g., natural uranium, lead, or tantalum)

Hydrodynamic Testing

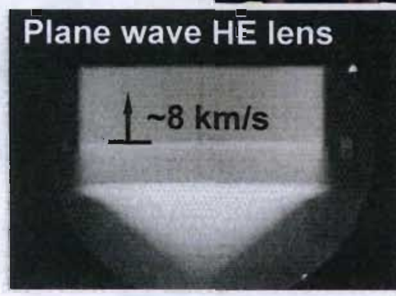
Shaped charge experiment illustrates the behavior of matter under the extreme pressures, shocks, and temperatures generated by high explosives



Radiographs showing the formation of the penetrating shaped charge jet illustrate why these experiments are called "hydrotests" → **Metals seem to flow like liquids when driven by a high explosive detonation**

Hydrotest Diagnostics

- Pin diagnostics are used to measure implosion velocity and symmetry
  - *Pin dome placed inside pit*
  - *Oscilloscopes record arrival times*
- Flash x-ray radiography is used to image various aspects of implosion
- High-speed optical photography



Nuclear Testing

Operating conditions of a nuclear weapon exist no where else and cannot be fully replicated in a lab setting

- Temperatures > 100 million degrees
- Material velocities > 1 million miles per hour
- Pressures > 10 million atmospheres
- Time scales measured in nanoseconds

1030 US and 24 Joint US/UK tests

- 839 Underground
- 210 Atmospheric
- 5 Underwater

Nuclear Test Diagnostics

Prompt Diagnostics:

- Nuclear device emits radiation (neutrons, gamma rays, and x-rays)
- Measured by various experiments consisting of line-of-sight pipes, detectors, cables, signal processing and data recording hardware

Reaction History: measures "alpha," the exponential growth rate of neutrons (or gammas) in weapon

Diagnostic Rack

Radiochemistry:

- Small quantities of material placed at various locations in the device
- Transformed via neutron interactions
- Drillback recovers samples that are analyzed to assess performance

"Delta P" (ΔP): change in the ratio ^{238}Pu to ^{239}Pu


Slant rig drill

"How Archival Test Data Contribute to Certification, Mortensen et al., Los Alamos Science, No. 28 (2003).

Computer Codes

- *Computational Models* – sets of equations describing various weapons phenomenology and numerical solution techniques
  - » High explosive burn
  - » Radiation/Hydrodynamics
  - » Neutronics
  - » Thermonuclear burn
- *Physical Data* – unique for each material
  - » Neutron cross sections
  - » Equation of state
  - » Opacities
- *Nonnuclear and Nuclear Test Data* – needed to overcome our lack of full physics understanding (essential to calibrate knobs)

LANL Metropolis Center for Modeling & Simulation

Road Runner: world's first machine to operate at 1.105 Petaflops

B-61 Nuclear Bomb (>4000 parts)

Backup Slides

What's a MeV?

1 eV = kinetic energy acquired by an electron (or proton) as it moves through an electric potential of 1 Volt

$1\ eV = 1.602 \times 10^{-19}\ J$

$10^6\ eV$ = 1 Million electron volts (MeV)

$2.6 \times 10^{25}\ MeV = 1\ kt\ TNT_{eq}$

Although defined in terms of charged particles, the MeV is a convenient unit of energy when working with neutrons and nuclear reactions

Kinetic Energy, Mass, Speed

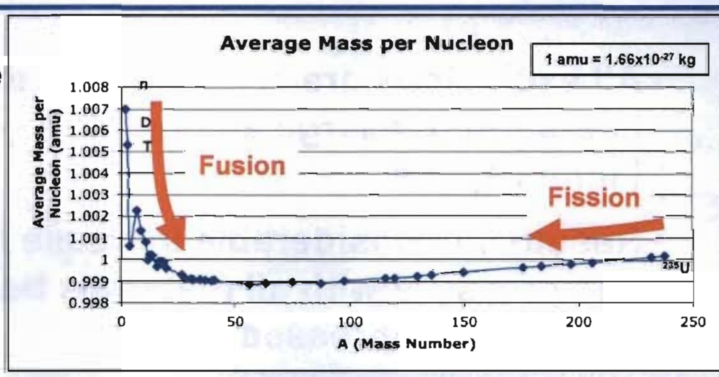
$$E_{kinetic} = (1/2)mv^2$$

Neutron Energy	Speed meters/sec	Speed miles/hour
0.025 eV	2200	4921
1 MeV	13.8×10^6	3.09×10^7
14 MeV	52×10^6	1.16×10^8

Nuclear Energy Release

Einstein's Relation:
mass-energy equivalence
$E = mc^2$

For ^{235}U fission - mass of reacting nuclei is greater than the mass of the product nuclei.



$$^{235}U + n \longrightarrow {}^{236}U \longrightarrow 2\ FPs + 3n$$

Mass before = (236 nucleons)(1.0002 amu/nucleon)
= 236.05 amu

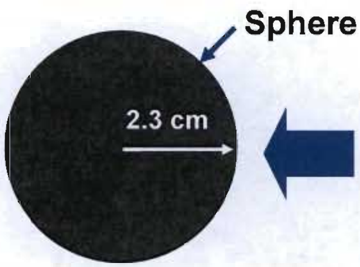
Mass after = (233 nucleons)(0.9992 amu/nucleon)
+ (3 nucleons)(1.0087 amu/nucleon)
= 235.83 amu

Mass Change = 0.22 amu
$= 3.7 \times 10^{-28}$ kg
$= 8.2 \times 10^{-28}$ lb

Energy Release = 205 MeV

Comparative Energy Release

	Energy/Reaction	Energy density*
Combustion (Chemical)	4 eV	4.1×10^{4} J/cm^{3}
Fission	200 MeV	1.5×10^{12} J/cm^{3}



	Energy Available*	100 Watt (J/s) bulb would burn for:
72 g coal	2.2×10^{6} J (~1 lb. TNT)	~6 hours
or		
1 kg U	80×10^{12} J (19 kt TNT)	~25,370 years

* Complete combustion or fission is assumed

Explosions

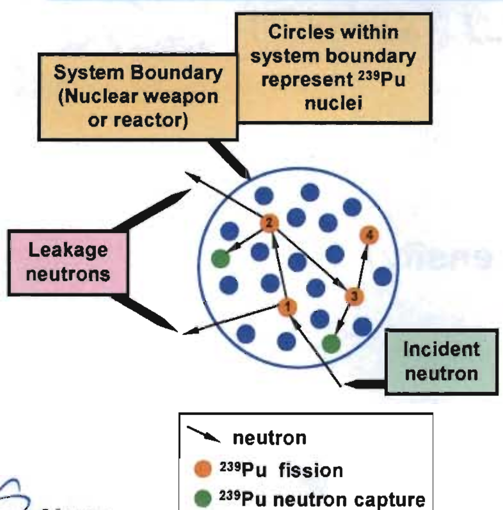
- All explosions are associated with the very rapid liberation of a large amount of energy within a limited space.
- Results in considerable increase in temperature and pressure with all materials being converted into hot, compressed gases
- These gases expand rapidly against surroundings, sending out a shock (or blast) wave which is responsible for most damage

Fission Explosions

- We have seen that fission (and large energy release) in ^{239}Pu and ^{235}U can be induced by an interaction with a neutron
- If an explosion is to be produced by fission energy release, then an essential condition is a very high neutron density (# neutrons/volume)
- A chain reaction is the mechanism for generating the required neutron population (and energy production) in a fission weapon

Criticality

***Criticality*: measure of how the number of neutrons (and energy release) in the system (e.g., nuclear weapon or reactor) will change over time**



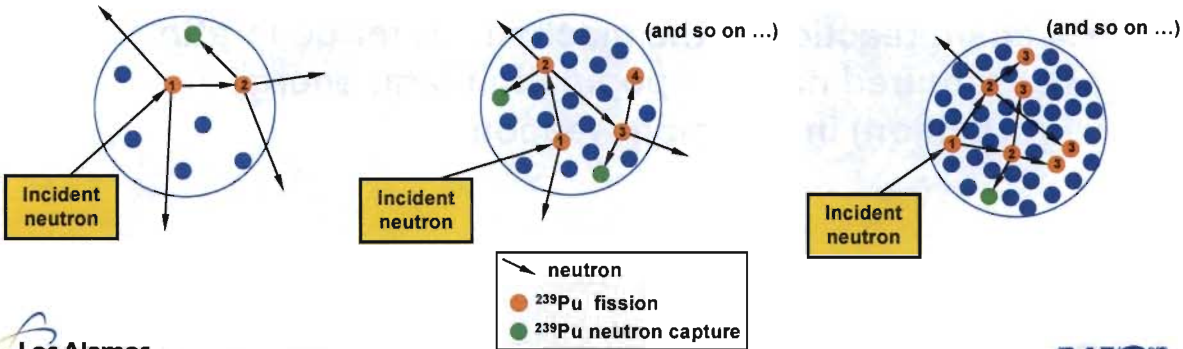
Change in Neutron Population (ΔN) = Neutrons Produced - Neutrons Lost

Production Mechanisms:
1) Fission reactions
2) Source
3) Other reactions e.g., (n,2n)

Loss Mechanisms:
1) Leakage
2) Neutron reactions e.g., (n,γ)

Criticality

ΔN < 0 Production < Loss	ΔN = 0 Production = Loss	ΔN > 0 Production > Loss
Subcritical system: number of neutrons (and energy release) decreases with time	**Critical system:** number of neutrons (and energy release) constant with time	**Supercritical system:** number of neutrons (and energy release) increases with time



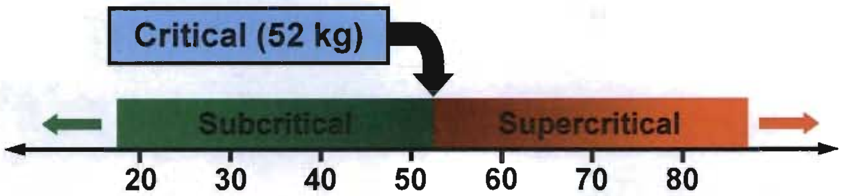
Factors Affecting Criticality

Critical mass: **amount of material needed to form a "critical system," just sustaining a steady-state fission chain reaction (constant neutron population and energy production)**

1. **Mass**
2. **Material**
3. **Compression (Density)**
4. **Shape**
5. **Surroundings**

Mass (Criticality)

Mass – for a given shape and density, a larger mass of material has a higher criticality



^{235}U bare sphere mass (kg)
ρ = 18.8 g/cm^3

For bare sphere:

$$\frac{\text{Loss}}{\text{Production}} \approx \frac{\text{Leakage rate}}{\text{Fission rate}} \approx \frac{\text{Surface area}}{\text{Volume}} \approx \frac{4\pi R^2}{(4/3)\pi R^3} \approx \frac{3}{R}$$

As radius (R) increases, neutron production from fission grows faster than leakage through surface.

Material (Criticality)

Material - ^{239}Pu has a smaller critical mass than ^{235}U

Bare sphere critical mass →

^{235}U
ρ = 18.8 g/cm^3
52 kg

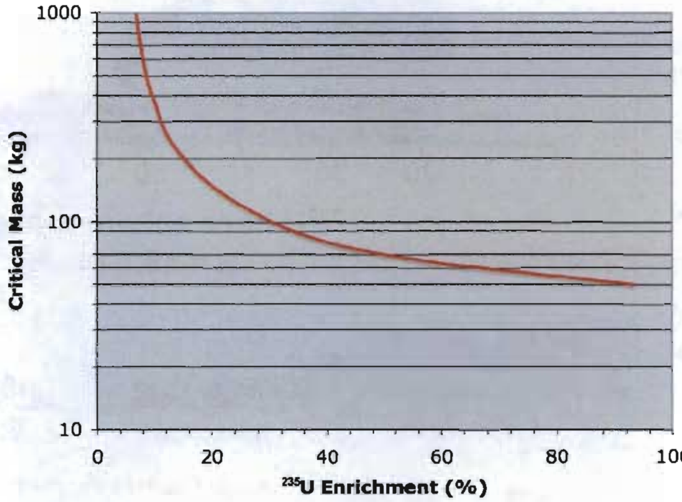
^{239}Pu (α-phase)
ρ = 19.5 g/cm^3
10.5 kg

This simply results from the more favorable nuclear properties of ^{239}Pu compared with ^{235}U (i.e., higher cross section and more neutrons released per fission)

Material (Criticality)

Material - materials enriched with higher concentrations of isotopes "more favorable" for fission have smaller critical mass

Higher enrichment in ^{235}U results in smaller critical mass

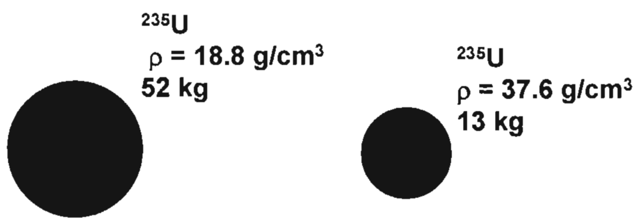


Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U, Paxton and Pruvost, LA-10860-MS (1986)

Compression (Criticality)

Compression – increases in material density result in smaller critical mass

Bare sphere critical mass ➡



$$M_{crit}^{compressed} = \frac{M_{crit}^{uncompressed}}{\eta^2} \quad \text{where} \quad \eta = \frac{\rho_{compressed}}{\rho_{uncompressed}}$$

Shape (Criticality)

Shape – for a given volume, shapes with smaller surface area have a smaller critical mass; sphere is optimal

Bare ^{235}U critical mass $\rho = 18.8\ g/cm^3$

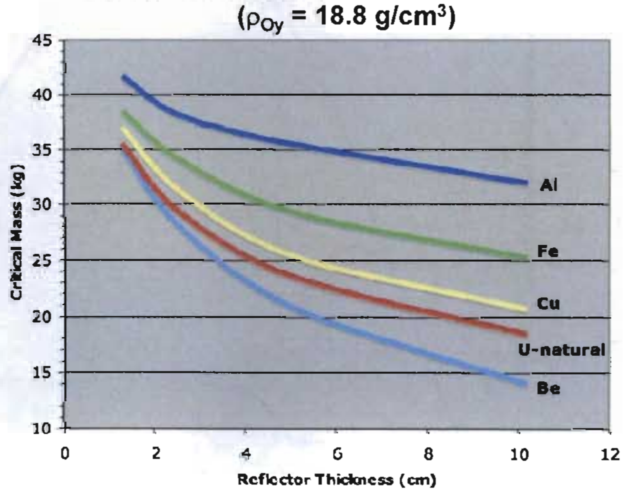
Sphere has the smallest surface area relative to its volume of any shape. This minimizes neutron leakage with respect to fission neutron production.

Surroundings (Criticality)

Surroundings – surrounding a system by a neutron reflector results in a reduced critical mass

Reflector reduces the leakage through the surface by scattering neutrons back into the fissioning material

Oy (93.5% ^{235}U) Spherical Critical Mass ($\rho_{Oy} = 18.8\ g/cm^3$)



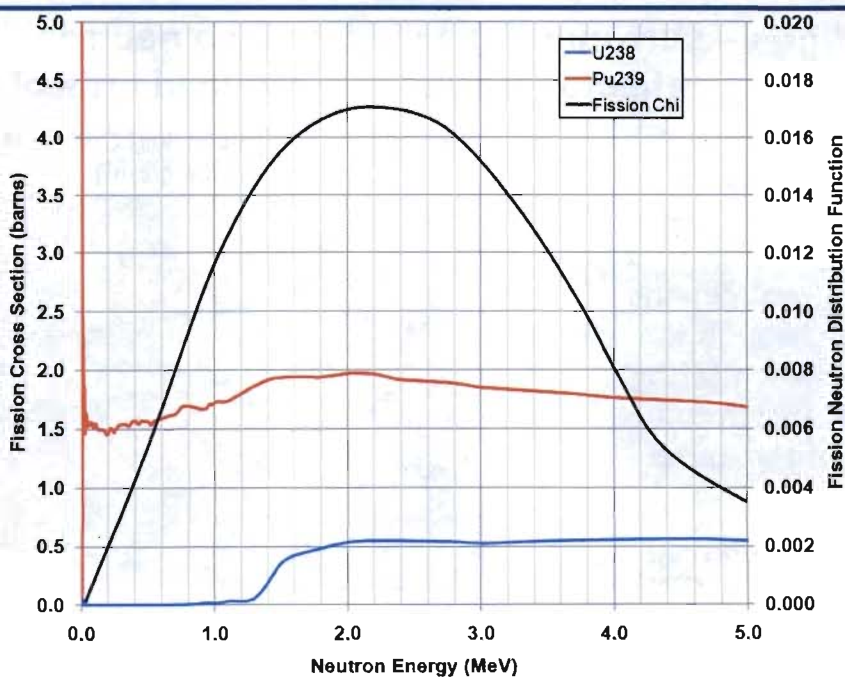
Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U, Paxton and Pruvost, LA-10860-MS (1986)

Critical Mass Summary

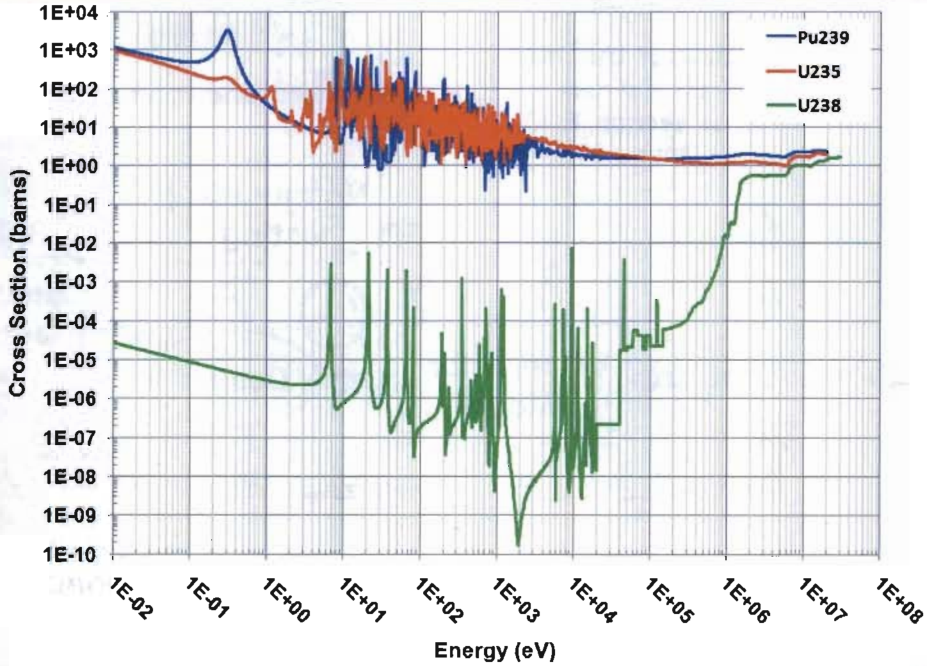
	Approximate Bare Sphere Critical Mass
^{235}U (18.8 g/cm^3)	52 kg
$^{239}Pu_{\delta}$ (15.7 g/cm^3)	16 kg
$^{239}Pu_{\alpha}$ (19.5 g/cm^3)	10.5 kg
^{233}U (18.4 g/cm^3)	15 kg
^{237}Np (20.4 g/cm^3)	57 kg

6 kg ^{237}Np sphere in the Planet critical assembly

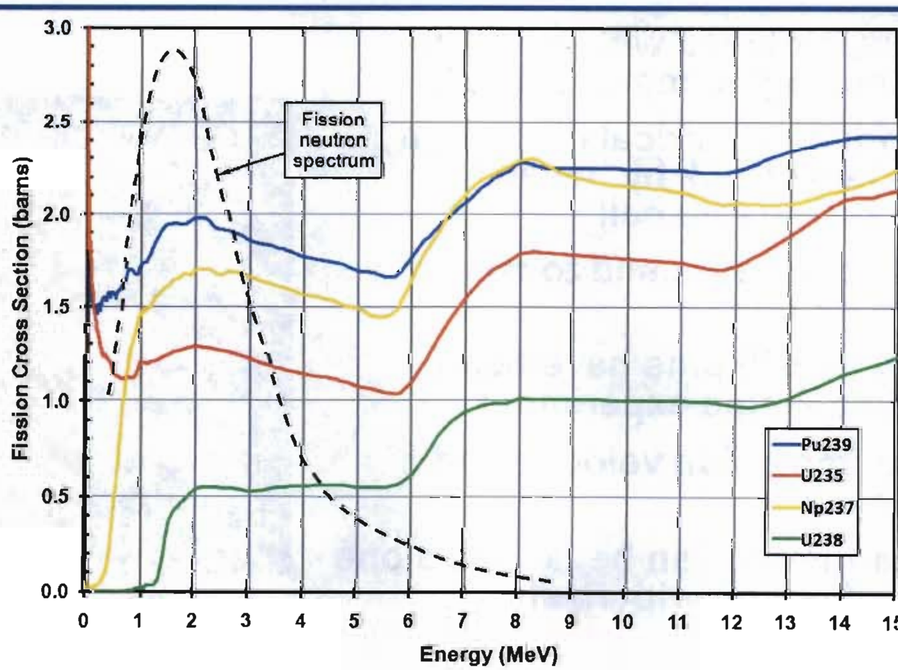
Fission Cross Sections



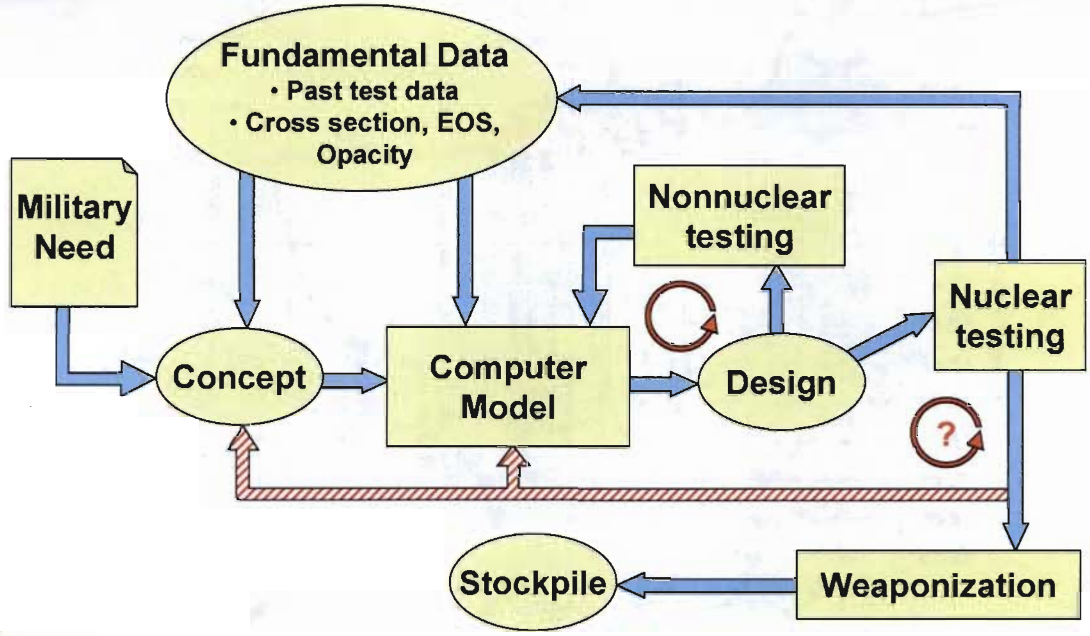
Fission Cross Sections



Fission Cross Sections



Traditional Design and Development



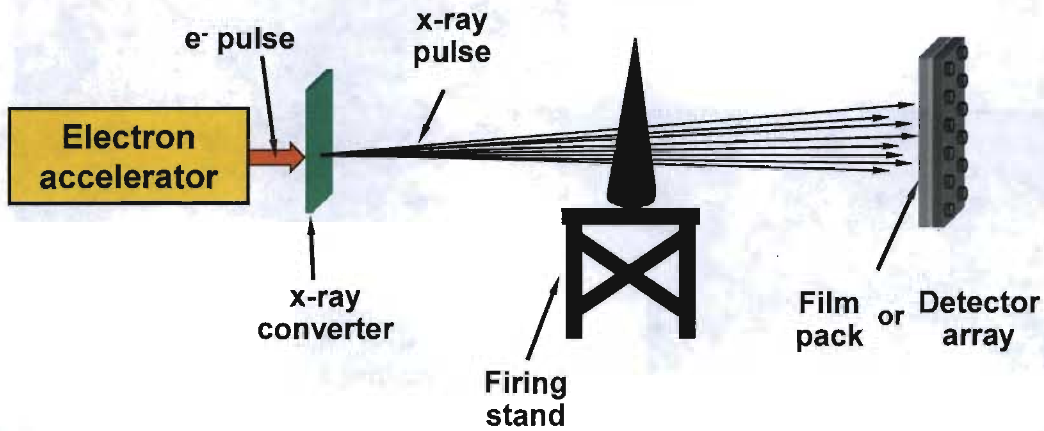
Pin Diagnostics

- Pin dome is placed within hollow shell of surrogate material in pit
- Pins produce electrical discharge signal when struck by inward moving surrogate shell
- Oscilloscopes are used to record timing of signals
- As many as 500 pins have been fielded in a single experiment
- Measure implosion velocity and symmetry
- Pin experiments can be fielded alone or in conjunction with flash radiography

Pin dome

Flash Radiography

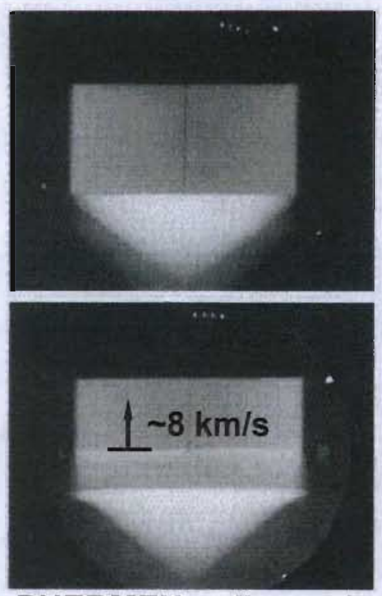
Use a high-energy electron beam to produce extremely short-duration intense bursts of high-energy x-rays capable of freezing the motion of a fast moving high-explosive-driven system



LA-UR 11-03126

Flash Radiography

X-ray pulse from flash radiography machine must be carefully timed with the experiment to capture the geometry at the time of interest



PHERMEX radiograph of plane wave lens

High-Speed Photography

Rotating mirror cameras

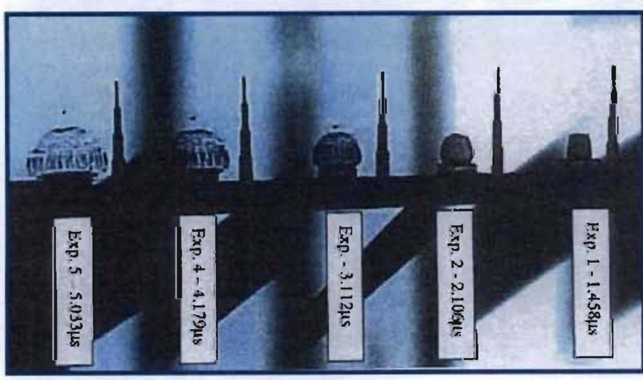
Framing camera (left)
Streak camera (right)

Inside a rotating mirror framing camera

High-Speed Photography

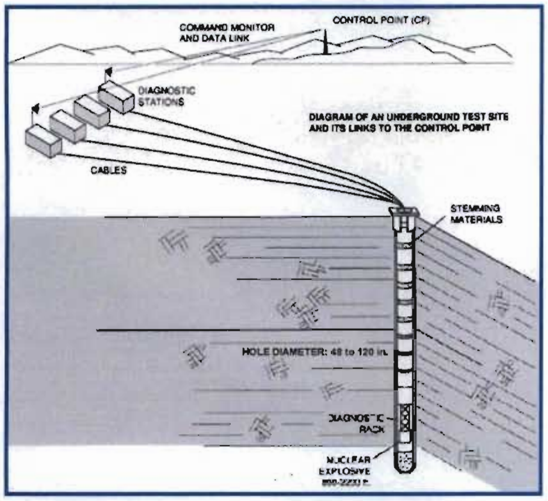
Rotating mirror framing camera images of exploding hand grenade (~1 million frames per second)

Courtesy of David J. Fisher and Rodney L. Robbs, Naval Weapons Center, China Lake, CA. Official US Navy photographs.



Electronic framing camera images of exploding detonator

Underground Testing



Weapon performance tests were performed in a vertical, drilled hole.